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THERMAL FLOWS AND CONDITIONS IN STONE WOOL MELT FIBERISATION

Roosa Juup 36652

Master´s Thesis in Thermal and Flow Engineering

Supervisor: Henrik Saxén

Faculty of Science and Engineering

Åbo Akademi University

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Abstract

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Thesis is done for the Laboratory of Thermal and Flow Engineering under supervision of Professor Henrik Saxén.

Keywords: heat loss, fiberisation, simulation

Different production processes are introduced first as well as various safety regulations which must be followed in the production.

Preface

This version of the master thesis is a shortened version. According to general public disclosure guidelines of Owens Corning, the client for this thesis, most of the thesis is business critical and cannot be published under any circumstances.

This master thesis has been done with at the Laboratory of Thermal and Flow Engineering at the Faculty of Science and Engineering, Åbo Akademi University. The initiative for the thesis came from the Paroc Group Oy. The company produces insulation wool and other products, which are related to insulation. They have been designing a new method for producing stone wool, and the thermal and flow conditions in the new production unit was of interest for a proper design. During the writing process, Paroc Group Oy became a part of Owens Corning, also an insulation manufacturer.

I want to thank Professor Henrik Saxén who was my supervisor and PhD Mikko Helle who helped me with the simulations. I also want to thank the project team for the project, especially project leader Ismo Kuokkanen, and my supervisors Peter Solin and Martin Slotte from Paroc Oy Ab for patience and cooperation. Finally, yet importantly, I want to thank my friends for encouraging and believing in me.

Turku, 2020

Roosa-Maria Juup

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About Paroc Group

Paroc Group is an international and leading manufacturer of energy-efficient stone wool insulation products in the Baltic Sea region (Paroc 1, 2017). The head office is located in Helsinki, Finland. Paroc has a few cornerstones in its operations: sustainable development, constant innovation, profitable growth and customer and personnel orientation (Paroc 1, 2017).

Paroc produces different types of insulation products: building insulation, marine and offshore insulation, technical insulation and acoustic products (Paroc 1, 2017). Building insulation and acoustic products include solutions for different types of customers and buildings and are mainly used for sound, thermal and fire insulation. Technical insulation offers value-added solutions for sound, thermal, fire and condensation insulation in buildings (HVAC), ship structures, industrial equipment (OEM), piping and industrial processes (Paroc 1, 2017).

1. The Production Process

The production processes for mineral wool vary. The biggest differences between the processes are in the fiberisation technique. A few different techniques of producing stone wool and glass wool are presented in section *2.3. Fiberisation*. Otherwise, the steps are similar within the processes. The production steps are raw material input, melting, fiberisation, binding, curing, cutting, packaging and storing (Gros, 2007). The last step is waste management, which is as important as the other steps.

1.1. Raw material

Various types of raw materials are used in mineral wool manufacturing. A few percent's change of components leads to products which have different features. The main raw materials for stone wool are rock and/or recycled material and other specific small components such as potassium carbonate and sodium carbonate (Eurima 2, 2011). In glass wool manufacturing sand, soda ash and limestone are used as raw materials. Also recycled materials, such as bottle glass or windows, are used in glass wool manufacturing (Eurima 2, 2011).

In general, raw materials are produced all over the world, for example in China. Paroc buys its raw materials from Europe. They are transported to Finland with cargo vessels and long-distance lorries. After arrival to the factory area, the raw materials are stored outside in huge piles or in storage buildings before they are used in the manufacturing process. In the production process, the raw materials are mixed by a specific formula to achieve all desired product features.

1.2. Melting

In the beginning of the production process, the raw materials have to be melted. There are different types of furnaces, such as cupola furnace and electric arc furnace, which can be used for this process. The cupola furnace has a refractory lining and a water-cooled shell refractor. The fuel used in cupola furnaces is coke, which is a particulate product obtained by dry distillation of coal. The electric arc furnace has three large graphite electrodes and these electrodes use alternating current for melting the raw material. The melt in this process is electrically charged. When the graphite electrodes are sunk in the melt, the melt will heat the raw material and melt it (Gros, 2007).

1.3. Fiberisation

In the traditional method for producing glass wool, the melt flows through one spinning disc (Figure 2). The fibres are formed by the melt because of the centrifugal force, with or without the help of stripping air (B. Sirok, 2008). After this, the fibres are directed to a conveyor belt and are mixed with a binder. In the stone wool production process, there are several spinning discs by which the fibres are formed, as seen in Figure 3. In TEL-fiberisation there is a combined system of techniques which are used both in glass and stone wool production processes.

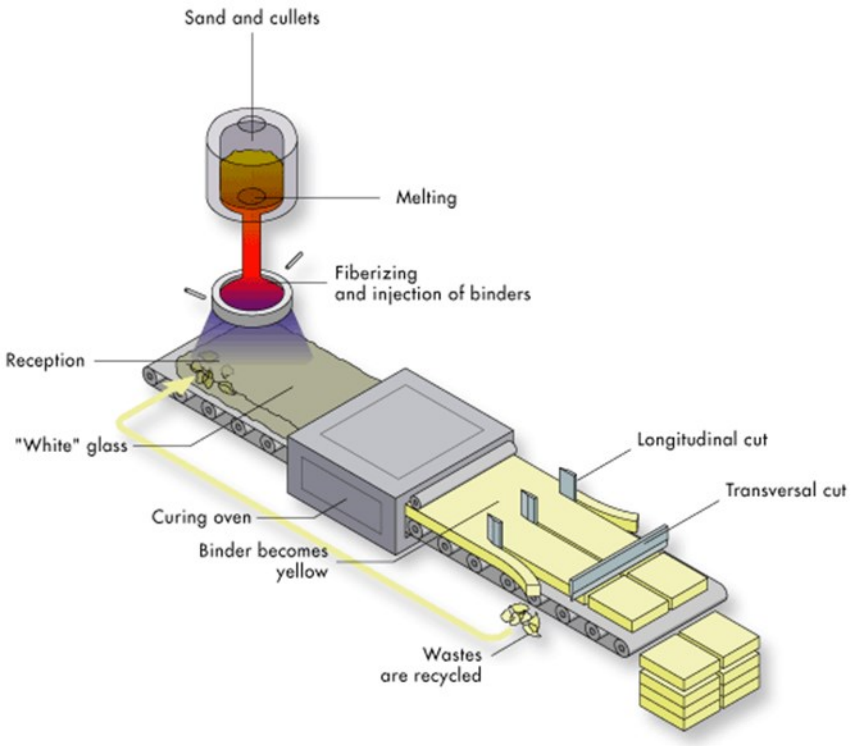

Figure 2. Traditional process of glass wool production (Eurima 2, 2011)

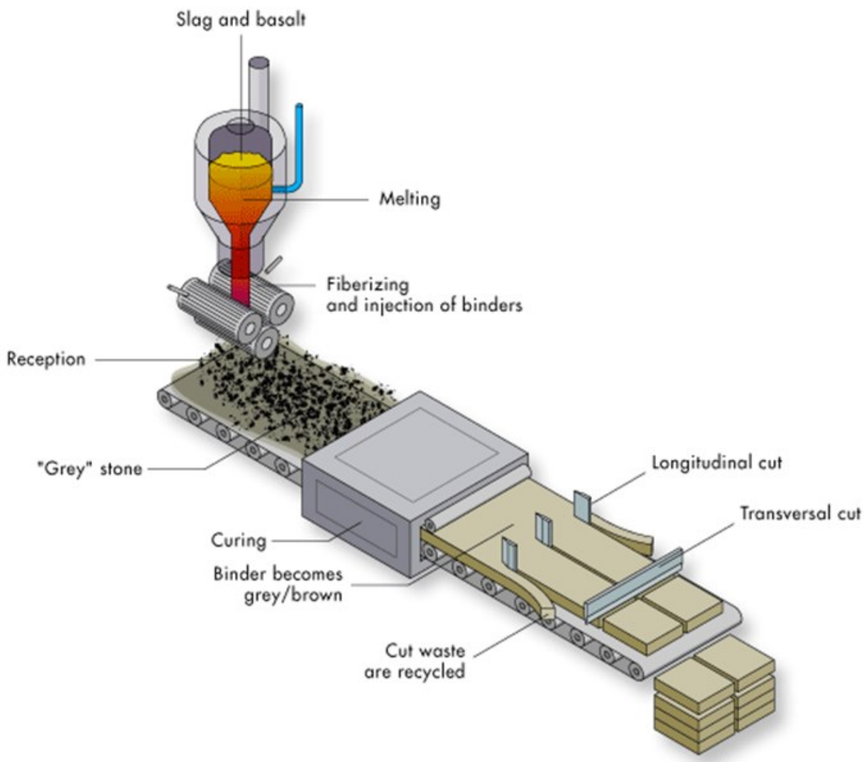

Figure 3. Traditional process of stone wool production (Eurima 2, 2011)

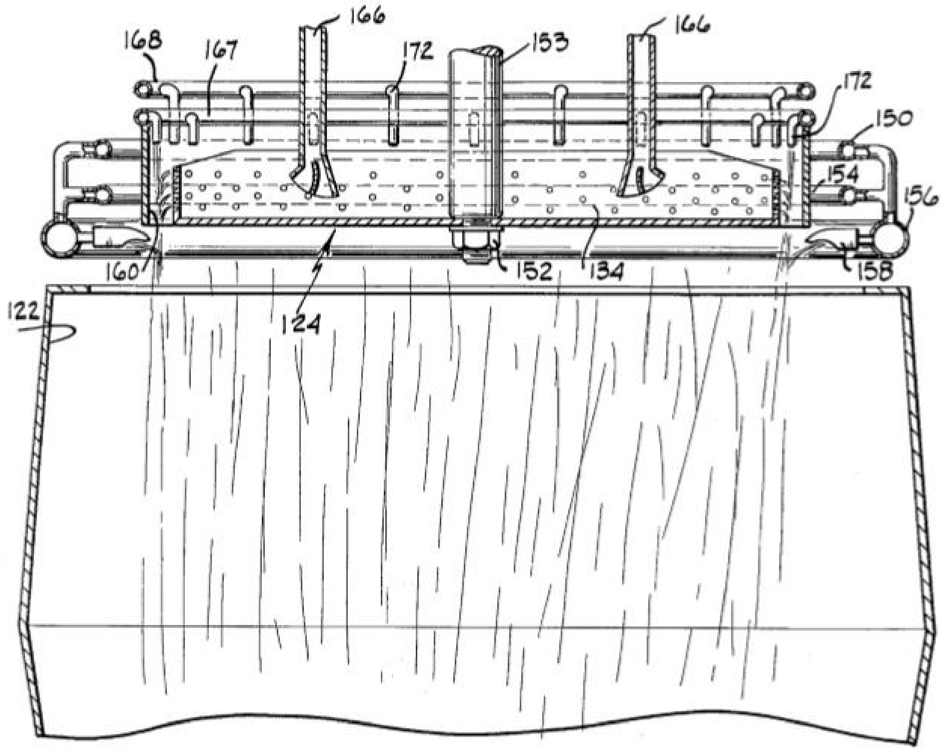

Figure 4. Example of stone wool production with one spinning disc (USA Patent No. 4,058,386, 1977)

1.4. Binding and Curing

After fiberisation small amounts of binding agents are added to the fibres, which helps to build the desired bulk density and structure of the product (Eurima 2, 2011). To harden the product the wool is heated in a curing oven to approximately 200 °C.

1.5. Cutting, Packaging and Storing

After curing, the mineral wool is cut to appropriate shape and size, usually into quadrangles, rolls or into a shape the customer requires. The rest of the wool which is not used, such as leftovers, is recycled, if possible. It is recommended to recycle everything to avoid extra waste and to be more environmentally friendly.

Mineral wool can be compressed while packed due to its elasticity, which saves storing and transporting space considerably. It also lowers the storing and transporting costs when much more mineral wool can be stored/transported at the same time. This has also a positive effect as it lowers the carbon emissions of the supply chain. Packed products can be stored both in storage halls and outside. If they are stored outside, the quality of the products must be checked before delivery to the customer. If the plastic packing material around the product is broken and the product has become wet, it is possible that the product quality is lower than for dry products.

1.6. Waste Management

The production process of mineral wool causes carbon emissions. The environmental impact is reduced with filters and after-burners, which clean the process gases. The process uses also a large amount of cooling water and to save water, costs and environment the cooling water is realised as a closed-circuit system. It means that the same water circulates in the process and is cooled down as needed to maintain an optimal temperature. A closed water circuit also guarantees that the potentially dirty and polluted water does not contaminate the environment.

Mineral wool manufacturers try to minimise all kinds of rest materials that they cannot recycle. Often the by-products and other waste can be used in some other field of industry and in this way make the production processes more sustainable.

2. Mineral Wool

Mineral wool is the common name for two types of insulation wool, glass and stone wool. Mineral wool is used as an insulation material in various areas. It has excellent thermal properties, which supports the efforts in Europe to save energy and therefore mitigate climate change (Eurima 1, 2011). Mineral wool also has other major advantages. Thermal insulation is one if the main aspects of mineral wool, but it also insulates against noise and slows down, or stops, the spread of fire. The stone wool produced with this new technology and new melt recipes must fulfil different criteria so that it can be sold as a safe product. Currently, there is little knowledge of the new product's solubility in human tissues. Other products produced by Paroc already fulfil all the EU directives. During the test runs, which are presented in Chapter 6, it was very important for all workers to use safety equipment, including respirator masks to avoid breathing small fibres into the lungs. The general safety certifications of mineral wool are listed in the next section.

2.1. Safety of mineral wool

Mineral wool is used as insulation material, so it must have different kinds of certifications. The effect of fibres produced with traditional methods on humans has been studied extensively. The International Agency for Research on Cancer (IARC), which is part of the World Health Organisation (WHO) has classified the mineral wool in line with European Union Directive 97/69/EC (Paroc Group 1, 2017). The directive sets requirements on safety and health for man-made vitreous fibres (MMVF) and states that "mineral wool fibres can be free of any suspicion of carcinogenicity if they are bio-soluble" (EUR-Lex, 1997). The carcinogenicity of MMWF products is classified according to the directive 97/69/EC into four categories:

1. Carcinogenic to humans
    - Asbestos
2. Probably carcinogenic
    - Ceramic fibre
3. Possibly carcinogenic
    - Not investigated insulation wools, those which are in research and development
4. Cannot be classified as carcinogenic
    - Includes PAROC stone wool products

In accordance with the EU classifications, produced mineral wool dissolves “at an acceptable rate” in the human body and that is why it can be labelled “non-classified” (Paroc Group 1, 2017). When the product is non-classified, it also means that it is considered non-carcinogenic. All products of Paroc fulfil the solubility requirements because Paroc has modified the chemical composition of the fibres according to all the regulations (Paroc Group 1, 2017).

There are different kinds of certifications and regulations that products produced by Paroc have to fulfil. The certifications and regulations are EUCEB certification, RAL Quality Mark and REACH regulation. The EUCEB and the REACH regulations are general certifications in Europe, but RAL Quality Mark is only needed in Germany.

2.1.1. EUCEB certification

The European Certification Board for Mineral Wool (EUCEB) verifies the conformity of the fibres in accordance to the directive 97/69/EC. The fibres are tested and if they meet all the criteria, the producer of the product will be given the right by EUCEB to put the EUCEB label on the packaging of the product (Paroc Group 1, 2017).

The criteria for the EUCEB certification are following and are listed on their web site (EUCEB, 2017):

1. Legal undertaking
2. Manufacturer's Declaration
3. Contract with Sampling Institute on test material sampling and monitoring of self-control
4. Exoneration certificate of the Biopersistence test
5. Short term Biopersistence test report
6. Confirmation of scientific expert that the fibre complies with EUCEB-exoneration criteria
7. Report of Analysis Institute on initial conformity inspection
8. Confirmation of scientific expert that initial conformity inspection complies with EUCEB range of exonerated fibres

2.1.2. RAL Gütezeichen (Quality Marks)

RAL Deutches Institut für Gütesicherung und Kennzeichnung (in English: RAL – German Institute for Quality Assurance and Certification) is a German certification system for technical delivery conditions (RAL 1, 2017). Word RAL comes from German words "Reichsausschus für Lieferbedingungen" which means in English the National Board for Delivery Conditions (RAL 1, 2017). RAL Quality Marks were invented to identify services and products that are provided or produced so that they fulfil all quality criteria (RAL 2, 2017).

The reason why Paroc has RAL Quality Marks in its products is that in June 2000 Germany added a ban on the production, circulation and use of "bio-persistent artificial mineral fibres" for technical insulation and for sound and heat absorption in buildings (Paroc Group 1, 2017). The criteria for RAL Quality Mark in mineral wool are not the same as in the European Directive 97/69/EU. When comparing mineral wool fibres produced in accordance with the European criteria and with the German exemption criteria, mineral wool fibres complying with the German criteria are more bio-soluble than fibres which comply the European criteria. The Gütegemeinschaft Mineralwolle (GGM) awards producers with the RAL Quality Marks and checks continuously that mineral wool fibres meet all the regulations. GGM is an independent body, a third party, which ensures that mineral wool products are safe to use, cost efficient, sustainable and healthy for human systems (GGM, 2017).

2.1.3. REACH Regulation

The REACH regulation is one the regulations and certifications which Paroc follows. The REACH regulation was published in the end of 2006 and entered into force in June 2007 (European Commission 2, 2016). “REACH” is an abbreviation from words Registration, Evaluation, Authorization and Restrictions of Chemicals (European Commission, 2016). REACH regulation, EC/1907/2006, was created to improve earlier identification of different chemical substances and their relevant properties. It also means that the REACH regulation aims to improve the protection of human health and also “to enhance innovation and competitiveness of the EU chemicals industry” (European Commission, 2016). The ECHA, The European Chemicals Agency, which manages all the aspects of the implementation of the REACH regulation, is located in Finland, in Helsinki (European Commission 2, 2016).

Consumers have the right to know what all products contain, including products that Paroc produces. Industrial products contain many different kinds of chemicals and the amounts of the chemicals can be very high. Also, there can be incomplete information about the chemicals and substances and, in worst case, they can be hazardous for the human system and health and for the environment. The idea with REACH regulation is that every information gap could be filled and, in that way, ensure that workers in the industry have access to get all this knowledge and information.

3. Heat Transfer Theory

Heat is an energy transfer between two bodies or media and occurs due to a temperature difference (Benson, 2004). The heat is usually denoted by Q and can be expressed by how much a body with mass m is heated, i.e., the temperature increase ΔT experienced, if a certain quantity of heat is transferred to it

$$Q = mc\Delta T \qquad (1)$$

where c is the specific heat capacity of the body.

As exceptions to this rule, during absorption or release of heat the substance may undergo a phase change without a temperature change. For such cases we can write

$$Q = mL \qquad (2)$$

where L is called the latent heat and it depends on the material and the type of phase change; for instance, L_v is the latent heat of vaporization and L_f is the latent heat of fusion.

The first law of thermodynamics says that "the internal energy U of a system can be changed either by the input of heat Q or by work W done by the system on its surroundings" (Benson, 2004). The formula is

$$\Delta U = Q - W \qquad (3)$$

Work W is negative in the expression because the system is doing the work; it would be positive if work is added to the system.

In an adiabatic process, the entire system is isolated and there is no heat exchange between with the environment, so $Q = 0$ and therefore $\Delta U = -W$. The only change is in the internal energy and it corresponds to the work done by the system.

3.1. Conduction Heat Transfer

Energy is transferred by conduction when there is an energy transfer from a body or a region with a higher temperature to a body or a region with a lower temperature, and a material is involved in the heat transfer (Holman, 1997). In other words, conduction occurs due to direct molecular collision between particles with different kinetic energy. If the body or media is cold, particles are moving slowly (lower kinetic energy) and if the body or media is warm, particles are moving rapidly (higher kinetic energy). The heat transfer rate through conduction, $\frac{dQ}{dt}$, is proportional to the temperature gradient, $\frac{dT}{dx}$, and to the cross-sectional area, A (Benson, 2004). The equation for heat transfer by conduction is called Fourier's law

$$\frac{dQ}{dt} = -\kappa A \frac{dT}{dx} \qquad (4)$$

where κ is the thermal conductivity which depends on the material. It measures the ability of how well a material conducts heat. κ is a positive quantity, and often approximated to be constant (as in equation 4). Since A is positive as well, $\frac{dT}{dx}$ must be negative to make $\frac{dQ}{dt}$ positive. $\frac{dQ}{dt}$ can also be denoted by q, so the equation can also be written

$$q = -\kappa A \frac{dT}{dx} \qquad (5)$$

In liquids and solids, conduction occurs by vibrational energy of the atoms.

When the system, for example of a bar where the heat is transferred, goes into a stable condition and the temperature has a linear variation with the distance along the bar, the equation can be also written as

$$\frac{dQ}{dt} = \kappa A \frac{T_H - T_L}{L} \qquad (6)$$

T_H here represents the high-end temperature and T_L the low-end temperature, while L is the length of the bar. Sometimes equation can be written as

$$\frac{dQ}{dt} = A \frac{\Delta T}{R} \qquad (7)$$

where the R is the thermal resistance of the sample. For the bar, it is calculated by dividing the length by the thermal conductivity, i.e., $R = L/\kappa$.

If there are several layers, for example two, of material the total heat conduction can be calculated from

$$\Delta T_1 + \Delta T_2 = \frac{1}{A}\left(\frac{L_1}{\kappa_1} + \frac{L_2}{\kappa_2}\right)\frac{dQ}{dt} \qquad (8)$$

The difference between this and equation 7 is that here the different layers have an individual temperature difference and thermal resistance. In this system the resistances are connected in series, so the total thermal resistance is the sum of all individual *R* values.

3.2. Radiation Heat Transfer

Radiation is a way of energy transfer without any involved medium (Benson, 2004). Every body will radiate heat to its surroundings, so even though a hot body will radiate more on a cold, the cold body will also radiate on the hot. The total effect will still be that more heat will be transported from the warmer body to the colder body. According to thermodynamic considerations, an ideal thermal radiator, or so called black body, emits energy "at a rate proportional to the fourth power of the absolute temperature of the body and directly proportional to its surface area" (Holman, 1997). The equation for this is

$$q = \frac{dQ}{dt} = e\sigma AT^4 \qquad (9)$$

where A is the surface area, T is the temperature, and σ if the The Stefan-Boltzmann constant, which has the value of 5,669x10^{-8} W/m^{2}xK^4. In equation (9), e is called the emissivity and depends on the nature of the surface and has a value between 0 and 1. If the emissivity approaches unity, the emission is maximum and the body behaves like a black body. For example, a deep mat black surface has an emissivity of ~0.95 while that of a shiny metallic body is about 0.1 (Holman, 1997). If the emissivity is low, the body reflects a lot vice versa. If equation 9 is presented without emissivity, it is called the Stefan-Boltzmanns law of thermal radiation (Holman, 1997) which applies to a perfectly black body.

A body is always an emitter and absorber in radiation heat transfer. If a small (convex) body at T_1 is surrounded by a large “surface” which is considerably bigger, at at temperature T_2, the net rate of radiated heat by the body is

$$q = \frac{dQ}{dt} = \varepsilon\sigma A(T_1^4 - T_2^4) \quad (10)$$

Equation 10 is special case and does not apply in general. For more general cases the net heat exchange by radiation has to be derived using view factors that express how much of the outgoing emission from one body “hits” the other.

3.3. Convection Heat Transfer

In convection, the heat transfers in a fluid, for example water or air. This kind of heat transfer is called convection (Gonzalez, 2015). In natural convection the motion of the fluid is induced by the heat transfer, e.g., “the fluid above a hot surface expands, becomes less dense, and rises” (Gonzalez, 2015). In convection heat transfer, the heat transfers firstly by conduction and secondly by fluid flow because the energy stored in the fluid moves with the fluid.

The equation for the overall effect of convection is

$$q = \frac{dQ}{dt} = hA(T_w - T_\infty) \quad (11)$$

which is the same as Newton´s law of cooling (Holman, 1997).

In equation 11, T_w is the temperature of a hot body which releases heat and T_∞ is the temperature of the bulk surrounding fluid. The quantity h is the convection heat transfer coefficient, which describes the efficiency of the heat transfer. Sometimes the heat transfer coefficient is called the film conductance because it has a relation in the conduction process at the wall surface in the thin stationary layer, the film, of the fluid. The convection heat transfer coefficient h can be calculated for limiting cases and simple systems, but for most practical systems the only way to obtain its value is to determine it experimentally.

The viscosity of the fluid has an effect on the convection heat transfer in addition to the fluid's thermal properties, such as specific heat and thermal conductivity (Holman, 1997). The reason for this is that the velocity profile of the fluid is influenced by viscosity and it also influences the energy transfer rate in the region nearby the wall. The flow can be turbulent or laminar and it depends on the velocity and viscosity of the fluid. The flow is laminar when the fluid flows in parallel layers without any mixing and the fluid has low velocity and high viscosity. In turbulent flow, there are unpredictable pressure and velocity changes and the fluid has high velocity and low viscosity. Also, the fluid particle movement is chaotic in turbulent flow.

There are four different types of convection heat transfer: free convection, forced convection, boiling and condensation (Holman, 1997). Free convection is just a natural convection, in forced convection there is a forced fluid flow; boiling and condensation are also natural phenomena.

4. Simulations

4.1. COMSOL Multiphysics

The simulations for this project were done with COMSOL Multiphysics version 5.3. COMSOL Multiphysics is “The Platform for Physics-Based Modeling and Simulation” (COMSOL Inc., 2017). COMSOL Multiphysics is a simulation tool for chemical, fluid flow, electrical and mechanical applications. It is based on advanced numerical methods for modelling problems based on physics and then simulating them. COMCOL Multiphysics allows the user account for multiphysics or coupled phenomena.

During this project, there were many of challenges with COMSOL because it was a totally new program for the author. Furthermore, the computer was not effective enough, so all the simulations had to be run on another computer, which was more effective and had larger memory. This computer was, however, used by another person so the runs could not be freely made.

5. Discussion

Fiberisation in stone wool production is a complicated process. Many different kinds of parameters must be right so that the fibre is suitable for the wool production. In shipbuilding it is very important to have light materials because otherwise the total weight of the ship can be too high.

Stone wool production is heavily regulated because stone wool insulation is used in construction work and therefore in contact with humans.

All these simulations and calculations give a somehow realistic picture of the fiberisation process. Calculations done with MATLAB showed realistic values of heat loss with different parameters. One of the challenges will be the cooling water. The cooling water temperature will rise during the wool manufacturing, not much, but enough and it must be cooled down again. The manufacturing process needs a lot of cold water and if it possible to cool down the used cooling water, it will both save manufacturing costs and environment.

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